

# Direct photons from Au+Au collisions at RHIC: QGP vs. hot hadronic gas

A. K. Chaudhuri\*

Variable Energy Cyclotron Centre,  
1/AF, Bidhan Nagar, Kolkata 700 064, India

We have analysed the preliminary PHENIX data on the transverse momentum distribution of direct photons in 0-20% centrality Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. In ideal hydrodynamics, data are explained if Au+Au collision produces Quark-Gluon-Plasma at the temperature  $T_i=400$  MeV, at an initial time  $\tau_i=0.6$  fm. PHENIX data are not explained in the alternate scenario when Au+Au collisions produces hot hadronic gas at temperature  $T_i \leq 220$  MeV at an initial time  $\tau_i \leq 5$  fm.

PACS numbers: PACS numbers(s):25.75.-q,12.38.Mh

In Au+Au collisions at RHIC, one observe a dramatic suppression of high  $p_T$  hadrons [1, 2, 3, 4]. The suppression is more in central than in peripheral collisions. It is also established that high  $p_T$  suppression is a final state effect, a parton before fragmenting in to hadrons suffers energy loss in a dense matter, leading to suppressed production [5]. High  $p_T$  suppression together with the observation that bulk of the hadron production data ( $p_T$  spectrum and elliptic flow etc.) are well described in a *ideal* hydrodynamic model [6, 7], strongly support the idea that RHIC has produced thermalised matter at very high energy density. However it is not certain whether the matter produced is strongly interacting Quark-Gluon-Plasma (sQGP) as predicted in lattice QCD calculations. Hadrons, being strongly interacting, are emitted from the surface of the thermalised matter and carry information about the freeze-out surface only. They are unaware of the condition of the interior of the matter and can provide information about the deep interior only in an indirect way. In a hydrodynamic model, one fixes the initial conditions of the fluid such that the "experimental" freeze-out surface is correctly reproduced. In contrast to hadrons, photons being weakly interacting, are emitted from whole volume of the matter. Throughout the evolution of the matter, photons are emitted. Conditions of the produced matter, at its deep interior, are better probed by the photons.

Recently PHENIX collaboration published their measurements of direct photons in different centrality ranges of Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV [8]. pQCD model calculation of direct photons in p+p collisions, multiplied with the thickness function, correctly reproduces the data in all the centrality ranges of collisions. Transverse momentum distribution of direct photons in different centrality ranges of collisions scale with the number of binary collisions. Apparently the direct photon results are in direct contradiction with high  $p_T$  suppression observed in Au+Au collisions. *Partons fragmenting in to photons do not suffer energy loss in contrast to partons fragmenting in to hadrons.* Moreover,

very good description of the published data with pQCD photons donot leave any room for thermal photons, which are expected to be emitted in large numbers from the thermalised matter.

Measurement of direct photons is very challenging, more so at low  $p_T$ . The huge background from  $\pi^0$  decay, dominate the spectra and proper algorithm for background subtraction is very important. Very recently PHENIX collaboration improved upon the analysis technique for photon measurement. Compared to the conventional method the new method improves both the signal to background ratio and the energy resolution. In QM2005, PHENIX collaboration presented the (preliminary) result of their new analysis [9]. With the new analysis technique, direct photon yield in the low  $p_T$  range (1-4 GeV), in 0-20% centrality Au+Au collisions is increased substantially. pQCD predictions no longer can explain the data. Direct photons in excess of pQCD (hard) photons are possibly from a thermal source. The PHENIX (preliminary) direct photon data thus provides the first opportunity to measure the initial condition of the matter produced in RHIC Au+Au collisions, at deep interior.

In the present paper, in a hydrodynamic model, we have analysed the PHENIX (preliminary) direct photon data. Procedure for obtaining photon spectra in a hydrodynamic evolution is well known [10]. We have solved the hydrodynamic equations  $\partial_\mu T^{\mu\nu} = 0$  for a baryon free gas assuming cylindrical symmetry and boost-invariance. We have considered two possible scenarios: (i) Au+Au collisions produce QGP as the initial state and (ii) Au+Au collisions produces hot hadronic gas. In the first scenario produced QGP expands, cools, undergoes 1st order phase transition at critical temperature ( $T_c$ ), enters a mixed phase, remain in the mixed phase till all the quark matter is converted into a hadronic matter then cools to freeze-out temperature. In the second scenario the hot hadronic gas expands, cools till the freeze-out. In both the scenarios, photons are emitted throughout the evolution and their yield in integrated over the space-time volume. The second scenario is very important for unambiguous detection of QGP. Direct photons are very strange probe. Theoretical predictions [11] indicate that they are emitted *equally well* from the QGP and from

---

\*E-mail: akc@veccal.ernet.in

the hot hadronic phase. Only in a narrow transverse momentum window around 3 GeV, the two phases may be distinguished. Indeed, direct photons measured at SPS energy in S+Au and in Pb+Pb collisions [12, 13] also raised high hope of detecting QGP. However, it was later found that the SPS energy data are well explained in models without QGP [14, 15].

In the present calculation we have used the bag model equation of state for the QGP phase,  $p_q = a_q T^4 - B$  with  $a_q = 42.25\pi^2/90$ . The hadronic equation of state was generalized to include all the mesonic resonances with mass  $< 2$  GeV. The cut off 2 GeV is rather arbitrary and we verify that the results do not depend on the value of cut-off significantly. The bag constant  $B$  was obtained from the Gibbs condition  $p_{QGP}(T_c) = p_{had}(T_c)$ . The critical temperature ( $T_c$ ) and the freeze-out temperature ( $T_F$ ) are assumed to be 180 MeV and 100 MeV respectively.

Photon emission rate from QGP and from hot hadronic gas are well known. For the single photons from hadronic gas we include the following processes,

- (a)  $\pi\pi \rightarrow \rho\gamma$ , (b)  $\pi\rho \rightarrow \pi\gamma$ , (c)  $\omega \rightarrow \pi\gamma$ , (d)  $\rho \rightarrow \pi\pi\gamma$   
(e)  $\pi\rho \rightarrow A_1 \rightarrow \pi\gamma$

rates for which are calculated in [16, 17]. Photon emission rates from QGP are calculated in [18, 19, 20, 21].

Hydrodynamic models require initial time ( $\tau_i$ ) and initial energy density profile ( $\varepsilon_i(r)$ ).  $\tau_i$  is essentially the thermalisation time beyond which hydrodynamic is applicable. RHIC data on elliptic flow as well as hadron  $p_T$  spectra require very short time scale of thermalisation  $\tau_i=0.6$  fm [6, 7]. In the first scenario, when QGP is produced in the initial state, we use this value as the initial time. The PHENIX (preliminary) direct photon data are in the 0-20% centrality range of collisions. In this centrality range, the average number of binary collisions is  $\langle N_{binary} \rangle \approx 779$ . We have assumed that 0-20% centrality Au+Au collision corresponds to central collisions of nuclei  $A_{eff}$ , such that the average number of binary collisions is reproduced. With  $T_{AA}(b=0) \approx \frac{A^2}{\pi R^2} = \frac{A^2}{\pi(1.12A^{1/3})^2}$ , we obtain  $A_{eff} \approx 143$ . For the initial energy density profile we use a Woods-Saxon form with radius  $R_{eff}=5.85$  fm (corresponding to nucleus  $A_{eff}=143$ ). For the diffuseness parameter we use  $a = 0.54$  fm. The central value of the energy density could be obtained by fitting the PHENIX preliminary data. However, presently we do not attempt exact fit to the data. Rather we have calculated the thermal photon yield with three values of central energy density,  $\varepsilon(r=0)=27.8, 47.1$  and  $75.1$  GeV/fm<sup>3</sup> corresponding to initial temperature  $T_i=0.35, 0.40$  and  $0.45$  GeV respectively.

Results of our calculation are shown in Fig.1. The three dotted lines are the thermal photons from initial QGP at temperature 350, 400 and 450 MeV respectively. In Fig.1, pQCD (hard) photons [22] are shown as the dash-dotted line. Sum of thermal and pQCD photon yield are shown as the solid lines. pQCD photons alone can not explain the PHENIX data throughout the  $p_T$

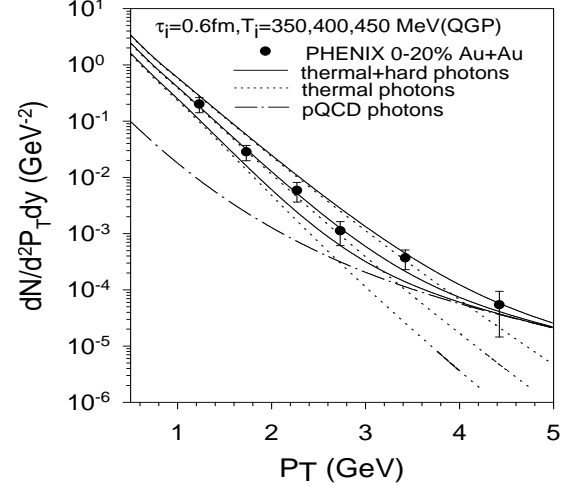


FIG. 1: PHENIX (preliminary) transverse momentum distribution of direct photons in 0-20% centrality Au+Au collisions. The dotted lines are thermal photons from QGP with initial temperature 350, 400 and 450 MeV (bottom to top), thermalised at  $\tau_i=0.6$  fm. The dash-dotted line is the pQCD photons. Solid lines are the sum of the pQCD and thermal photons.

range. It explains the data at large  $p_T$  but underestimates the yield at low  $p_T$ . PHENIX (preliminary) direct photon data require thermal photons. Thermal photons dominate the photon spectra at low  $p_T$ . As seen in Fig.1, if the initial QGP is formed at temperature  $T_i=350$  MeV, the PHENIX data are underpredicted. The data are over predicted for initial temperature  $T_i=450$  MeV. PHENIX (preliminary) direct photon data are explained if the initial temperature is  $T_i=400$  MeV. The analysis suggests that the PHENIX (preliminary) direct photon data in 0-20% centrality Au+Au collisions are explained if Au+Au collisions produce QGP with central temperature 400 MeV at an initial time of 0.6 fm.

Let us now consider the photon yield in the second scenario when Au+Au collisions produce hot hadronic gas. As it is well known, photon emission rate from QGP and from hot hadronic gas are very similar. Degeneracy of resonance hadron gas is also of the same order as that of a QGP. Thus it is expected that a hot hadronic gas thermalised at  $\tau_i \sim 0.6$  at an initial temperature of  $T_i \sim 400$  MeV will give a similar description to the PHENIX data, as it is obtained in the 1st scenario. However hadronic gas at such a high temperature is physically unacceptable. Density of the gas is very large  $\rho_{hadron} \sim 50$  fm<sup>-3</sup>. Hadrons can not retain their identity at such a high density. What is the acceptable limit of initial temperature of the hot hadronic gas? Recent lattice QCD calculations indicate that critical temperature of confinement-deconfinement phase transition is  $T_c = 190 \pm 10$  MeV [23]. Possibly hadrons can re-

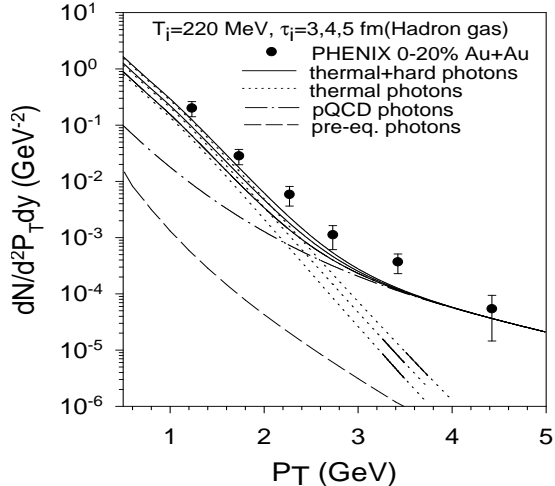


FIG. 2: PHENIX (preliminary) transverse momentum distribution of direct photons in 0-20% centrality Au+Au collisions. The dotted lines are thermal photons from initial hot hadronic gas at initial temperature of 220 MeV, thermalised at  $\tau_i=3,4$  and 5 fm (from bottom to top). pQCD photons are shown as the dash-dotted. The solid lines are the sum of the pQCD and thermal photons. Photons from a pre-equilibrium QGP are shown as the dash-dot-dot line.

tain their identity still at higher temperature. We choose  $T_i=220$  MeV as the physically acceptable value for the initial temperature of the hot hadronic gas. At this temperature density of the hadron gas is  $\rho_{hadron} \sim 1.7 fm^{-3}$  just below the limit  $\rho_{hadron} < 2 fm^{-3}$  so that the hadrons retain their identity. Now what should be the thermalisation time scale for a hot hadronic gas? Will it be as small as that of a QGP? If the hadronic gas at initial temperature of 220 MeV thermalises at the same time scale (0.6 fm) the PHENIX (preliminary) direct photon data are not explained. However, thermalisation time scale for a hadronic gas can be longer. Indeed, very small thermalisation time scale ( $\tau_i \sim 0.6 fm$ ) obtained for a QGP is a puzzle in heavy ion physics and is not understood properly. If the parton-parton collisions are responsible for thermalisation, the thermalisation time is significantly longer. Calculations performed within the 'bottom-up' thermalisation scenario including  $2 \leftrightarrow 2$  and  $2 \leftrightarrow 3$  processes estimate  $\tau_i > 2.6 fm$  [24, 25]. Only mechanism for short thermalisation scale is plasma instability in soft modes of the gluon field [26]. Due to rapid longitudinal expansion of the system, the momentum spectrum of partons quickly become anisotropic, the width of the longitudinal momentum distribution become narrower than the width of the transverse momentum distribution  $\langle \Delta p_L^2 \rangle \ll \langle \Delta p_T^2 \rangle$ . A transverse chromo-electric field develop, which further enhances the fluctuations in the parton momentum distribution. Anisotropic parton momentum distribution can cause magnetic (transverse)

instabilities, which can be very efficient in thermalising the system. Characteristic inverse time scale for instability development is roughly of the order of  $gT$  for sufficiently anisotropic momentum distribution. Thermalisation time scale of a hot hadronic gas is expected to be greater than that of a QGP as it is likely that in a hot hadronic gas, thermalisation will be driven by collisional process rather than by the plasma instabilities. Plasma instabilities, in hot hadronic gas, being electromagnetic in nature, will not be efficient to thermalise the system rapidly ( $\alpha < \alpha_s$ ). In [27] thermalisation of linear sigma model fields were studied numerically. In the model, sigma model fields interact with a heat bath. Irrespective of the initial field configuration, sigma model fields thermalises in the time scale  $\sim 5$  fm. In resonance hadronic gas thermalisation process will be faster as number of fields greatly exceed that of the sigma model. A reasonable estimate will be  $\tau_i \sim 1-5$  fm.

In Fig.2 photon yield from the hot hadronic gas, with initial temperature  $T_i=220$  MeV for three time scale of thermalisation,  $\tau_i=3,4$ , and 5 fm are shown (the dotted lines). Even with large thermalisation scale,  $\tau_i=5$  fm, PHENIX data are not explained if Au+Au collisions produces hot hadronic gas at an initial temperature of 220 MeV. The data remain underpredicted by a factor of two or more. The hadronic state can not produce the required number of photons.

With large thermalisation time,  $\tau_i=5$  fm, the fluid matter spends considerable time in the pre-equilibrium stage. Thus while pre-equilibrium photons may not be important if Au+Au collisions produces QGP ( $\tau_i=0.6$  fm), they may be important if the collisions lead to hot hadronic gas formation ( $\tau_i=5$  fm). To unequivocally reject the hot hadronic gas scenario it is important to estimate the pre-equilibrium photons. Unfortunately emission of photons from a pre-equilibrium hadronic gas is not studied. However, photon emission from a pre-equilibrium QGP has been studied earlier [28, 29]. Pre-equilibrium photons are order of magnitude less than equilibrium photons. Following [29] we have estimated the photon yield from a chemically non-equilibrated partonic system with initial conditions dictated by the HIJING simulation for RHIC Au+Au collisions. The partonic system achieved kinetic equilibrium by the time  $\tau_{iso}=0.31$  fm at temperature of 570 MeV. At  $\tau_{iso}=0.31$  fm, gluon and quarks fugacities are 0.09 and 0.02 respectively. We have considered only longitudinal expansion. In Fig.2, pre-equilibrium photons (integrated over the time scale 0.31 to 5 fm) are shown as the dashed line. Photons from pre-equilibrium stage contribute insignificantly. The reason can be understood easily. The photon emission rate is weighted by the fugacities which remain at low values in the time scale integrated. With transverse expansion, pre-equilibrium emission at large  $p_T$  will increase, however, the increase would never be large enough to reckon them. If the pre-equilibrium hot hadronic gas contribute to the same order as the pre-equilibrium QGP, we can safely ignore them. Even if pre-

equilibrium photons from the hot hadronic gas exceed that from the pre-equilibrium QGP by a factor of 10, they still can be neglected. We conclude that PHENIX (preliminary) direct photon data are not explained if Au+Au collisions produces a physically acceptable hot hadronic gas, with initial temperature less than 220 MeV at an initial time less than 5 fm.

To summarise, we have analysed the preliminary PHENIX data on the transverse momentum distribution of direct photons in 0-20% centrality Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. Two scenarios are considered, (i) Au+Au collisions produces a QGP and (ii) Au+Au collisions

produces hot hadronic gas. PHENIX (preliminary) direct photon data are explained in the first scenario if QGP is produced at initial time  $\tau_i=0.6$  fm at an initial temperature  $T_i=400$  MeV. PHENIX data are not explained in the alternate scenario if the hot hadronic gas is produced with initial temperature less or equal to 220 MeV at an initial time 5 fm or less. The data remain underpredicted. As the hot hadronic gas at higher temperature or with longer thermalisation time is physically unacceptable, we conclude that PHENIX (preliminary) direct photon data are explained only if QGP is produced in 0-20% centrality Au+Au collisions.

- 
- [1] BRAHMS Collaboration, I. Arsene *et al.*, Nucl. Phys. A **757**, 1 (2005).
  - [2] PHOBOS Collaboration, B. B. Back *et al.*, Nucl. Phys. A **757**, 28 (2005).
  - [3] PHENIX Collaboration, K. Adcox *et al.*, Nucl. Phys. A **757** (2005), in press [arXiv:nucl-ex/0410003].
  - [4] STAR Collaboration, J. Adams *et al.*, Nucl. Phys. A **757** (2005), in press [arXiv:nucl-ex/0501009].
  - [5] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077.
  - [6] P. F. Kolb and U. W. Heinz, arXiv:nucl-th/0305084.
  - [7] P. F. Kolb, U. W. Heinz, P. Huovinen, K. J. Eskola and K. Tuominen, Nucl. Phys. A **696**, 197 (2001) [arXiv:hep-ph/0103234].
  - [8] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **94**, 232301 (2005) [arXiv:nucl-ex/0503003].
  - [9] H. Buesching [the PHENIX Collaboration], arXiv:nucl-ex/0511044.
  - [10] H. Von Gersdorff, L. D. McLerran, M. Kataja and P. V. Ruuskanen, Phys. Rev. D **34**, 794 (1986).
  - [11] S. Turbide, R. Rapp and C. Gale, Phys. Rev. C **69**, 014903 (2004) [arXiv:hep-ph/0308085].
  - [12] R. Santo *et al.* [WA80 Collaboration], *Prepared for NATO Advanced Study Workshop on Hot Hadronic Matter: Theory and Experiment, Divonne-les-Bains, France, 27 Jun - 1 Jul 1994*
  - [13] M. M. Aggarwal *et al.* [WA98 Collaboration], Phys. Rev. Lett. **85**, 3595 (2000) [arXiv:nucl-ex/0006008].
  - [14] A. K. Chaudhuri, J. Phys. G **29**, 235 (2003) [arXiv:nucl-th/0012058].
  - [15] A. K. Chaudhuri, Phys. Rev. C **51**, 2889 (1995).
  - [16] H. Nadeau, J. I. Kapusta and P. Lichard, Phys. Rev. C **45**, 3034 (1992).
  - [17] L. Xiong, E. V. Shuryak and G. E. Brown, Phys. Rev. D **46**, 3798 (1992) [arXiv:hep-ph/9208206].
  - [18] J. I. Kapusta, P. Lichard and D. Seibert, Phys. Rev. D **44**, 2774 (1991) [Erratum-ibid. D **47**, 4171 (1993)].
  - [19] P. Aurenche, F. Gelis, R. Kobes and H. Zaraket, Phys. Rev. D **58**, 085003 (1998) [arXiv:hep-ph/9804224].
  - [20] P. Aurenche, F. Gelis and H. Zaraket, Phys. Rev. D **61**, 116001 (2000) [arXiv:hep-ph/9911367].
  - [21] P. Aurenche, F. Gelis and H. Zaraket, Phys. Rev. D **62**, 096012 (2000) [arXiv:hep-ph/0003326].
  - [22] B. Jager, A. Schafer, M. Stratmann and W. Vogelsang, Phys. Rev. D **67**, 054005 (2003) [arXiv:hep-ph/0211007].
  - [23] S. D. Katz, arXiv:hep-ph/0511166.
  - [24] R. Baier, A. H. Mueller, D. Schiff and D. T. Son, Phys. Lett. B **502**, 51 (2001) [arXiv:hep-ph/0009237].
  - [25] R. Baier, A. H. Mueller, D. Schiff and D. T. Son, Phys. Lett. B **539**, 46 (2002) [arXiv:hep-ph/0204211].
  - [26] S. Mrowczynski, arXiv:hep-ph/0511052.
  - [27] A. K. Chaudhuri, Phys. Rev. C **65**, 014905 (2002) [arXiv:hep-ph/0106209].
  - [28] C. T. Traxler and M. H. Thoma, Phys. Rev. C **53**, 1348 (1996) [arXiv:hep-ph/9507444].
  - [29] A. K. Chaudhuri, J. Phys. G **26**, 1433 (2000) [arXiv:nucl-th/9808074].